Cryogenic Filtering For Use In 2D Topological Insulators

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Background

The nascent field of quantum computation has the potential to radically improve the way computers are constructed and applied. One untapped method for harnessing the potential for a stable quantum computer is in topological insulators (TIs), where the discovery of stable Majorana bound states may lead the way to substantial advances in the creation of topological quantum computation, as well as in the stability of quantum computation as a whole.

However, the study of these mesoscopic electronics systems introduce problems not typical of more conventional electrical configurations. In particular, transport measurements of electrons are heavily influenced by the thermal energy those electrons possess. If the electrons in the signal lines are not properly thermalized, their energy fluctuates randomly on orders of magnitude much larger than that of the data of interest, thus making any type of data collection or analysis impossible. This means that in order to take successful data, not only must one's equipment be cooled to a temperature on the order of mK, but the electrons passing through the equipment must also be cooled to this temperature. Additionally, like most sensitive circuits, one must design a circuit configuration that accounts for shielding from external electrical noise. Therefore, a circuit designer must attend to both electrical filtration and thermalization in these systems. Designing, creating, and improving these systems is the goal of this project.

Research Question:

How do RC- and Pi-filtration impact overall signal attenuation for cryogenic electronics measurements?

Design

Two electrically filtering printed circuit boards (PCBs) were used in this project: a Pi-Filter, and an RC-Filter, whose basic layouts are pictured below. The RC boards were designed using a combination of two layers of resistors and capacitors of varying values, along with prepackaged low-pass filters with a predefined frequency cutoff (below, left). The Pi-filters were also designed using these prepackaged low-pass filters, but across all stages (below, right).

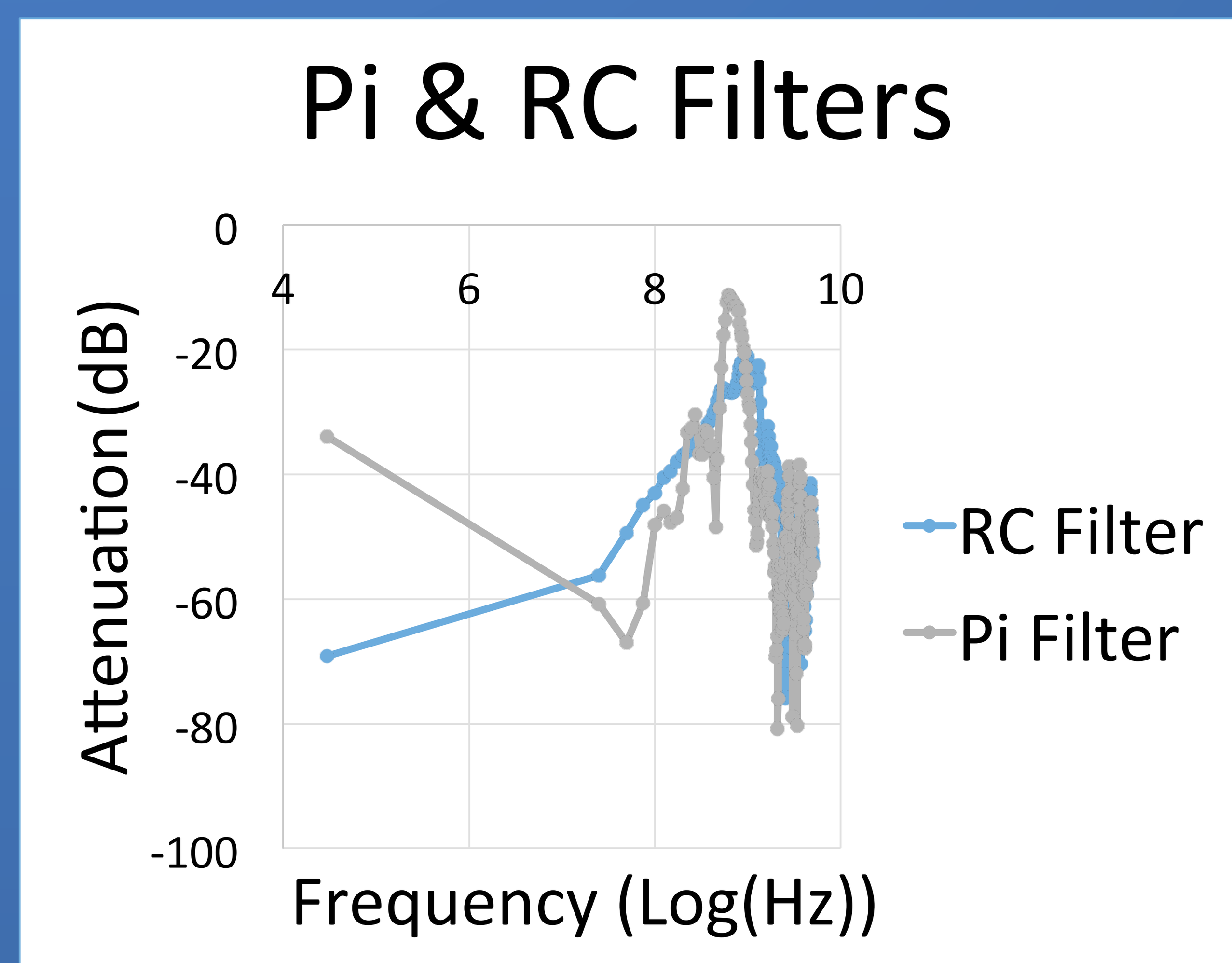
The boards were connected using nonmagnetic connecters attached to segments of a twisted-pair constantan wire loom, which was wrapped around cold posts inside a dilution refrigerator, where the measurements will take place, to assist with thermalization of the signals. Finally, all of the connectors were shielded in annealed, gold-plated copper boxes, which prevented any external electromagnetic noise from interfering with the system (below, top).

Results

After performing characteristics tests on each of the filters when loaded into the fridge, we were able to characterize the signal response rates of each of our filters (see the figure below). The attenuation scale given on the left indicates how much power was reduced by each filter, with -20 corresponding to a 10% reduction in power. For clarification, the signals we intend to test are at frequencies near or below 22kHz, so all noise above this value should be sufficiently attenuated.

We found that the composition of the Pi- and RC- filters greatly reduces noise in the 30kHz - 2.5MHz range, with higher frequencies in the GHz range also receiving attenuation from each filter. In particular, on the order of kHz, our signal attenuation, at ~-34 dB for the RC filter and ~-68 dB on the pi filter, is excellent: it corresponds to a factor of reduction of approximately $8\times10\uparrow-6$ of the electrical signal output at that frequency. We also found that our full circuit thermalizes to the base temperature of the fridge while the filters are installed, achieving the 10-20 mK temperatures required to collect data on our samples.

It should be noted that the setup used to perform measurements on our samples requires two signal lines, each containing its own Pi- and RC-Filter. This means that high-frequency fluctuations will be somewhat normalized for high frequency noise, since in principle the high frequency noise from each line can be compared and the background extracted from the sample. In this way, the attenuation for the high-frequency noise becomes sufficient for measurements on the samples.



Discussion

One caveat yet not mentioned about the configuration of the circuit is that additional stages beyond these filters will be implemented to perfect the measurements, especially with regards to thermalization. However, only slight tuning to the electrical noise of the sample will occur in subsequent stages in the dilution refrigerator, making the output of these filter critical to the circuit as a whole.

One issue that may have affected the results obtained from the filters, especially with regards to the slight transmission of high frequency noise (neat .3% at its peak) may be because of an alignment issue that the group encountered when assembling the gold-plated copper boxes and lids used to shield the filters. A thin gap on the order of a millimeter exists between the lids due to this alignment issue, so until this is resolved the data we take on these filters may not be exactly representative of how they may perform when appropriately shielded.

Overall, the filters perform appropriately enough to deliver electrically well-filtered signals to our samples in the desired frequency ranges, as well as contribute to the overall thermalization of the system. The group may now move forward with tests on its samples, now that the sensitive electrical and thermal requirements associated with low temperature measurements have been handled.

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